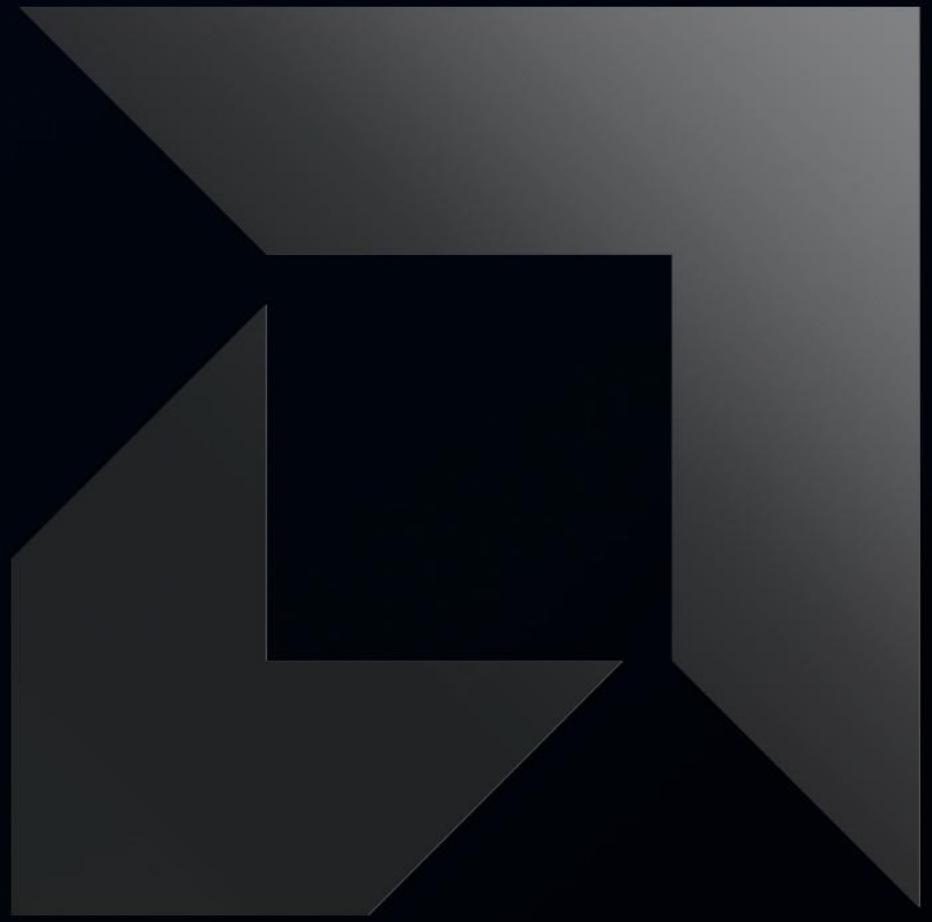

Introduction to OpenMP® Offload on AMD GPUs

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AMD @ Tsukuba University
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AMD
together we advance_

Motivation for OpenMP for GPUs

Fortran:

```
!$omp parallel do private(i) shared(Nl,…)
do i=1,Nl
  …
end do
!$omp end parallel
```

CPU examples

C/C++:

```
#pragma omp parallel for private(i) shared(Nl,…)
for(int i=0, i<Nl, i++){
…
}
```

- Why use OpenMP for porting to GPUs?
  - ✓ OpenMP is standardized
  - ✓ Portable code
  - ✓ Fortran, C, and C++ supported
- Many HPC codes are already OpenMP (+MPI) parallelized on CPUs
  - ✓ Porting requires only few code changes
  - ✓ Easy to learn
- Interoperability with HIP and ROCm libraries
  - ✓ Flexibility
- GPU code can be compiled for the CPU, too
  - ✓ Start porting before having access to GPUs
  - ✓ Majority of correctness checks possible without access to GPUs

Compilers – two major strands

Primary Support

- LLVM™ based
  - ROCm compilers provide support for both HIP and OpenMP®
    - hipcc -- /opt/rocm/bin
    - amdclang -- /opt/rocm/llvm/bin
  - AOMP: AMD OpenMP® research compiler for prototyping new features

Use LLVM based compilers for production (or Cray if available)

Functionality Only

- GCC based -- GNU Compilers
  - Provide offloading support to AMD GPUs (OpenMP®, OpenACC)
    - GCC 11 added offloading for the AMD MI100 GPUs
    - GCC 13 adds support for the AMD MI200 GPU series.
  - https://gcc.gnu.org/wiki/Offloading

amdflang-new beta pre-release of AMD Fortran compiler

Installed on aac6 to use in this training:

module load amdflang-new/

Module will set the following:

export FC=amdflang-new

AMD is working on a Fortran compiler and is ready to share a beta version. During the training, you will have hands-on access to the beta. Going forward, AMD will continue to provide early access via AFARs (Advanced Feature Access Releases) as improvements and features are added to the beta. **As with any beta, we are looking to gather feedback on functionality, usability and user experience.**

New Flang is released in the ROCm 7.0 version!

Blog post about next gen Fortran compiler: https://rocm.blogs.amd.com/ecosystems-and-partners/fortran-journey/README.html

PRE-PRODUCTION SOFTWARE: The software accessible on this training may be a **pre-production version**, intended to provide advance access to features that may or may not eventually be included into production version of the software. Accordingly, pre-production software **may not be fully functional, may contain errors, and may have reduced or different security, privacy, accessibility, availability, and reliability standards** relative to production versions of the software. Use of pre-production software may result in unexpected results, loss of data, project delays or other unpredictable damage or loss. Pre-production software is not intended for use in production, and your use of pre-production software is at your own risk.

Enabling OpenMP® on AMD Hardware

		LLVM		GCC	
Compiler Module ➡		amdclang/aomp/clacc		gcc/og	
		Command	Flags	Command	Flags
Language	C	amdclang clang	-fopenmp --offload-arch=<gfx###>	gcc	-fopenmp --foffload=-march=<gfx###>
	C++	amdclang++ clang++	-fopenmp --offload-arch=<gfx###>	g++	-fopenmp --foffload=-march=<gfx###>
	Fortran	amdflang(-new) flang(-new)	-fopenmp --offload-arch=<gfx###>	gfortran	-fopenmp --foffload=-march=<gfx###>

Offloading Target (CPU/GPU/GCD)	Architecture <gfx###>
AMD MI300 Series	gfx942
AMD MI200 Series	gfx90a
AMD MI100	gfx908
Native Host (CPU)	-fopenmp-targets=amdgcn-amd-amdhsa

Sample OpenMP® Makefile

```
EXEC = reduction
default: ${EXEC}
all: ${EXEC}

ROCM_GPU ?= $(strip $(shell rocminfo |grep -m 1 -E gfx[^0]{1} | sed -e 's/ *Name: *//'))

CC1=$(notdir $(CC))

ifeq ($(findstring amdclang,$(CC1)), amdclang)
  OPENMP_FLAGS = -fopenmp --offload-arch=$(ROCM_GPU)
else ifeq ($(findstring clang,$(CC1)), clang)
  OPENMP_FLAGS = -fopenmp --offload-arch=$(ROCM_GPU)
else ifeq ($(findstring gcc,$(CC1)), gcc)
  OPENMP_FLAGS = -fopenmp -foffload=-march=$(ROCM_GPU)
else ifeq ($(findstring cc,$(CC1)), cc)
  OPENMP_FLAGS = -fopenmp
  #the cray compiler decides the offload-arch by loading appropriate modules
  #module load craype-accel-amd-gfx942 for example
endif

CFLAGS = -g -O3 -fstrict-aliasing ${OPENMP_FLAGS}
LDFLAGS = ${OPENMP_FLAGS} -fno-lto -lm

${EXEC}: ${EXEC}.o codelet.o
        $(CC) $(LDFLAGS) $^ -o $@

# Cleanup
clean:
        rm -f *.o ${EXEC}
```

Sample OpenMP® CMakeLists

```
cmake_minimum_required(VERSION 3.21 FATAL_ERROR)
project(Memory_pragmas LANGUAGES CXX)

set (CMAKE_CXX_STANDARD 17)

if (NOT CMAKE_BUILD_TYPE)
   set(CMAKE_BUILD_TYPE RelWithDebInfo)
endif(NOT CMAKE_BUILD_TYPE)

string(REPLACE -O2 -O3 CMAKE_CXX_FLAGS_RELWITHDEBINFO ${CMAKE_CXX_FLAGS_RELWITHDEBINFO})
set(CMAKE_CXX_FLAGS_DEBUG "-ggdb")
if ("${CMAKE_CXX_COMPILER_ID}" STREQUAL "Clang")
   # using Clang
   set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -fopenmp --offload-arch=gfx942 -fstrict-aliasing")
elseif ("${CMAKE_CXX_COMPILER_ID}" STREQUAL "GNU")
   # using GCC
   set(CMAKE_CXX_FLAGS
       "${CMAKE_CXX_FLAGS} -fopenmp -foffload=-march=gfx942 -fstrict-aliasing -fopt-info-optimized-omp")
elseif (CMAKE_CXX_COMPILER_ID MATCHES "Cray")
endif()

add_executable(mem1 mem1.cc)
```

How we begin

- The first step in porting an application to use OpenMP® for offloading work to a GPU is to add a compute pragma/directive to a loop
- Choose one of the more expensive loops in your application for the first loop to add a compute pragma
  - This will give the most compute speedup to offset the slowdown from memory transfers to the GPU and back
  - Testing OpenMP® parallelism on the CPU can identify potential problems
  - Another quick test is to reverse the loop direction on a loop to see if there is an order required for correctness
- A profile of your existing code will help identify potential loops to offload to the GPU
- Pay attention to what data needs to be moved to enable the offloading

- While this appears simple, many complex physics applications can be difficult to approach
- You may want to try simpler loops first just to get some experience with the process

Running example for this presentation: saxpy

Declaration and
Initialization of arrays on CPU
in main routine (not shown)

```
void saxpy(float a, float *x, float *y, int N) {

#pragma omp parallel for
   for (int i = 0; i < N; i++) {
      y[i] += a * x[i];
   }

   printf("check output:\n");
   printf("y[0] %lf\n",y[0]);
   printf("y[N-1] %lf\n",y[N-1]);
}
```

This is the code we want to execute on a target device (i.e., GPU) with appropriate directives to be introduced next

This is for CPU: OpenMP® Pragma to run in parallel with multiple threads

WARNING: operations like saxpy should be done through an efficient library (e.g. hipblas) in production codes

If you prefer Fortran

```
subroutine saxpy(a, x, y, n)
   use iso_fortran_env
   implicit none
   integer,intent(in) :: n
   real(kind=real32),intent(in) :: a
   real(kind=real32), dimension(:),allocatable,intent(in) :: x
   real(kind=real32), dimension(:),allocatable,intent(inout) :: y
   integer :: i

   !$omp parallel do simd
   do i=1,n
       y(i) = a * x(i) + y(i)
   end do

   write(*,*) "plausibility check:"
   write(*,'("y(1) ",f8.6)') y(1)
   write(*,'("y(n-1) ",f8.6)') y(n-1)
end subroutine saxpy
```

Declaration and
Initialization of arrays on CPU
in main routine (not shown)

This is the code we want to execute on a target device (i.e., GPU) with appropriate directives to be introduced next

This is for CPU: OpenMP® directive to run in parallel with multiple threads

How to offload to the GPU: the `target` directive

- Transfer **control and data** from the host to the device
- Syntax (C/C++)

```
#pragma omp target [clause[[,] clause],…]
structured-block
```

- Syntax (Fortran)

```
!$omp target [clause[[,] clause],…]
structured-block
!$omp end target
```

- Clauses

```
device(scalar-integer-expression)
map([{alloc | to | from | tofrom}:] list)
if(scalar-expr)
```

NOTE: target will move the computation to the GPU, but **single thread only** instead of using the whole device. Occupancy will be <1%

But there is more to a GPU compute directive than just “target”

- We need to tell the compiler what hardware resources to use
- We also need to tell it how to spread out the work
- Sometimes the compiler can detect information and do the right thing, other times it cannot

- Despite all this possible complexity, most compute pragmas are simple one-liners to use all the hardware and distribute all the work

- `#pragma omp target teams distribute parallel for simd`

  or for Fortran

- `!$omp target teams distribute parallel do simd`

- C/C++ uses `pragmas` as directives to the compiler
- Fortran uses a comment syntax for its directives

- We‘ll go into each part of this pragma in the next talk

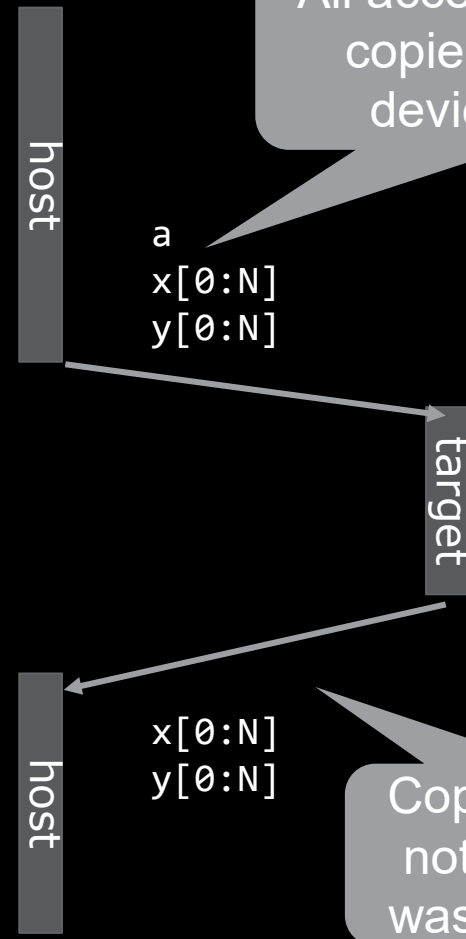
Example: saxpy_gpu_singleunit_static

Compiler does the work

```
int main(int argc, char *argv[]){
   int N=100000;
   float a=2.0f;
   float x[N], y[N];

   for (int i = 0; i < N; i++) {
      x[i] = 1.0f; y[i] = 2.0f;
   }

#pragma omp target teams distribute parallel for simd
   for (int i = 0; i < N; i++) {
      y[i] += a * x[i];
   }

   printf("check output:\n");
   printf("y[0] %lf\n",y[0]);
   printf("y[N-1] %lf\n",y[N-1]);
}
```

The compiler identifies variables that are used in the target region

All accessed arrays are copied from host to device and back.



Copying x back is not necessary. It was not changed.

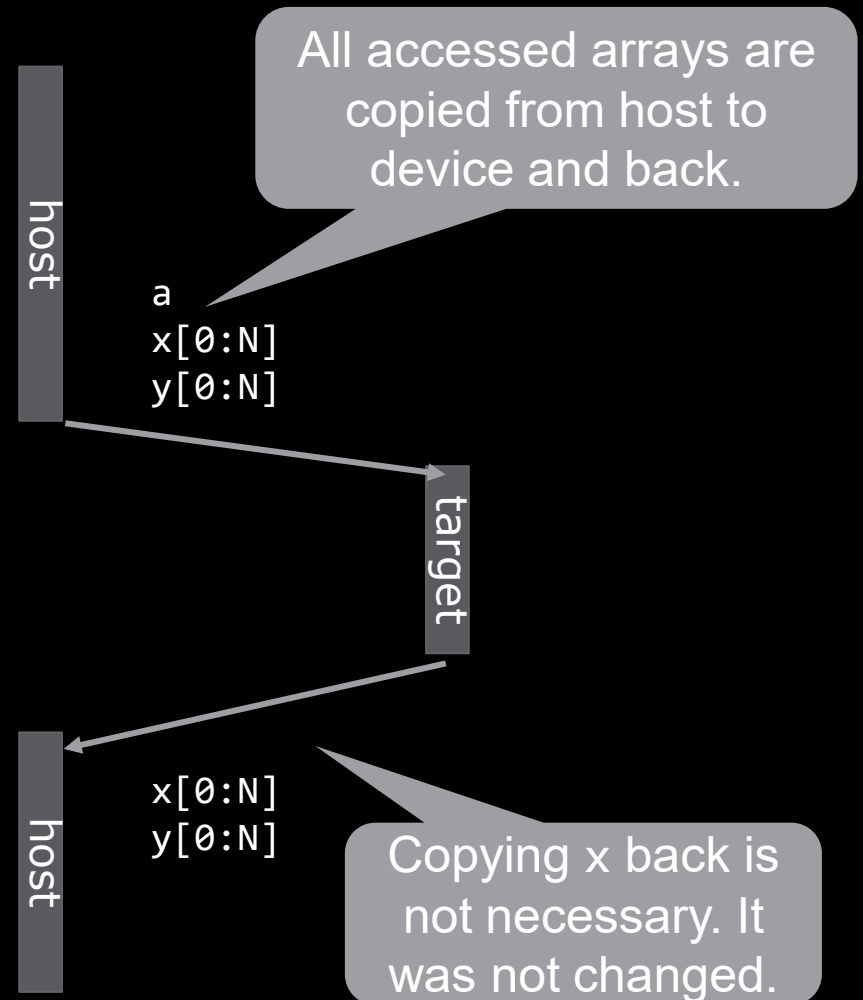
Example: saxpy_gpu_singleunit_dynamic

```
int main(int argc, char *argv[]){
   int N=10000000;
   float a=2.0f;

   float *x = (float *)malloc(N*sizeof(float));
   float *y = (float *)malloc(N*sizeof(float));

   for (int i = 0; i < N; i++) {
      x[i] = 1.0f; y[i] = 2.0f;
   }

#pragma omp target teams distribute parallel for simd
   for (int i = 0; i < N; i++) {
      y[i] += a * x[i];
   }

   printf("check output:\n");
   printf("y[0] %lf\n",y[0]);
   printf("y[N-1] %lf\n",y[N-1]);

   free(x); free(y);
}
```

The compiler identifies variables that are used in the target region but cannot get the sizes

Requires "export HSA_XNACK=1" or map clause

In Fortran allocatable arrays are mapped by default



A note on the simd clause

- C/C++
  - `#pragma omp target teams distribute parallel for simd`
- Fortran
  - `!$omp target teams distribute parallel do simd`

- Note on the compute construct:
  - The `simd` clause doesn't do anything with the AMD OpenMP compiler and can be dropped.
  - Nvidia also doesn't use it.
  - Cray used to be the most common compiler where it was used, but they are moving to drop it as well.
  - But…there are still OpenMP compilers such as the Intel® compiler that recognize it and use it.
  - So…for maximum portability, we include it. But you may want to drop it depending on the systems you plan to run on.
  - If you use the `simd` clause, you will get warnings about not being able to vectorize during compilation. These are harmless and can be ignored.

Other compute clauses -- loop

- The loop clause was added as a simpler option that gives the compiler more freedom in implementing the parallelism for a for loop

  ```
  #pragma omp target teams loop
  ```

  - Reduces the pragma complexity
  - Compilers may not optimize (or implement) this case as well because it is new.

- ROCm will generate an optimized target region implementation for AMD GPUs to use

  ```
  #pragma omp target teams loop
  ```

  Instead of

  ```
  #pragma omp target teams distribute parallel for
  ```

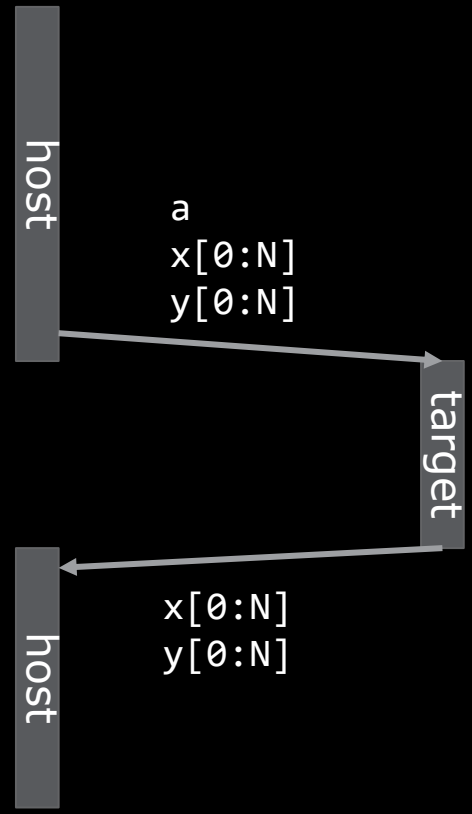
  In OpenMP 6.0, replaces `teams distribute parallel for`

- The loop clause will be coming soon for the AMD next generation flang compiler.

Example: saxpy

Simpler “loop” pragma/directive is equivalent to
`#pragma omp target teams distribute parallel do simd`

```
void saxpy(float a, float *x, float *y, int N) {
#pragma omp target teams loop
   for (int i = 0; i < N; i++) {
      y[i] += a * x[i];
   }

   printf("check output:\n");
   printf("y[0] %lf\n",y[0]);
   printf("y[N-1] %lf\n",y[N-1]);
}
```




```
amdclang -fopenmp --offload-arch=$GPU_ARCH ...
```

Nested Loops – collapse clause

- `collapse(n)` clause will collapse nested loops into one parallel construct. It can generate more work groups to help fill up the GPUs
  - Originally, only perfectly nested loops could be collapsed (no extra lines of code between the for/do loops)
  - This constraint has been relaxed and some lines of code are now acceptable both before and after the inner loop
  - This example can be collapsed by the ROCm LLVM™ OpenMP® compiler (and LLVM trunk)

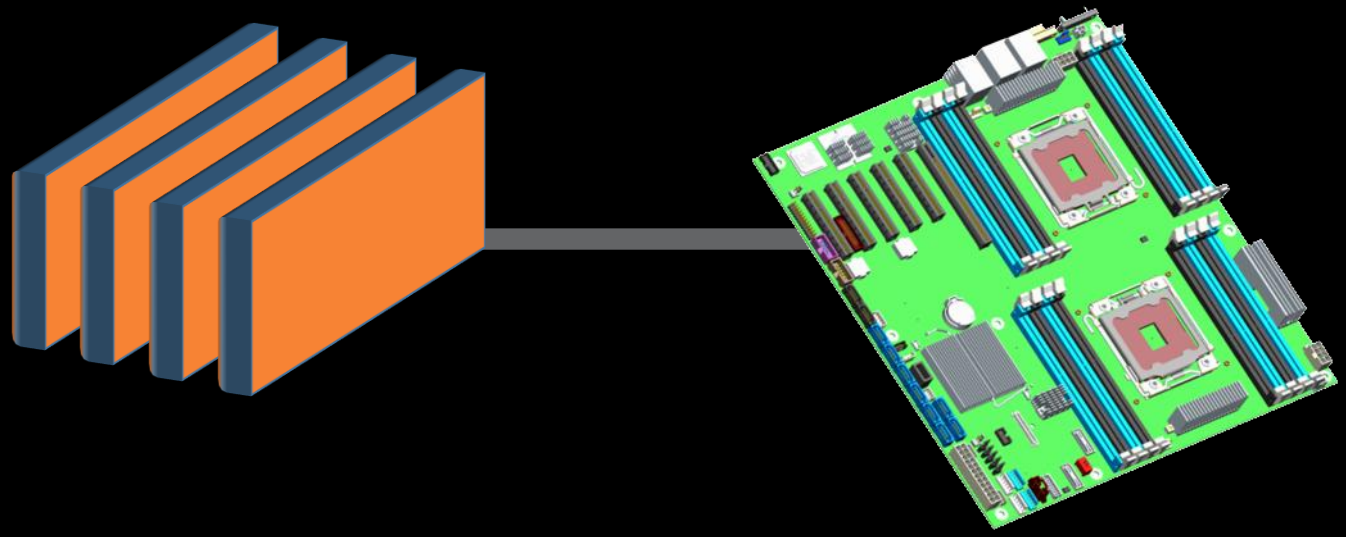
```
int A[N][N];
int B[N][N];
int e = -1;
#pragma omp target teams distribute
parallel for collapse(2)
for (int j = 0; j< N; j++) {
    e++;
    for (int i = 0; i < N; i++)
        a[j][i]=b[j][i]+e;
    e++;
}
```

Nested Loops – collapse clause example

```
subroutine saxpy(a, x, y, m, n)
   use iso_fortran_env
   implicit none
   integer,intent(in) :: m, n
   real(kind=real32),intent(in) :: a
   real(kind=real32), dimension(:,:),allocatable,intent(in) :: x
   real(kind=real32), dimension(:,:),allocatable,intent(inout) :: y
   integer :: i, j
   real(kind=real64) :: start, finish

   !$omp target teams distribute parallel do collapse(2)
   do j=1,n
     do i=1,m
       y(i,j) = a * x(i,j) + y(i,j)
     end do
   end do

   write(*,*) "plausibility check:"
   write(*,'("y(1,1) ",f8.6)') y(1,1)
   write(*,'("y(m,n) ",f8.6)') y(m,n)
end subroutine saxpy
```

Collapse clause causes the work to be distributed from both loops

Optimizing Data Transfers is Key to Performance on discrete GPUs

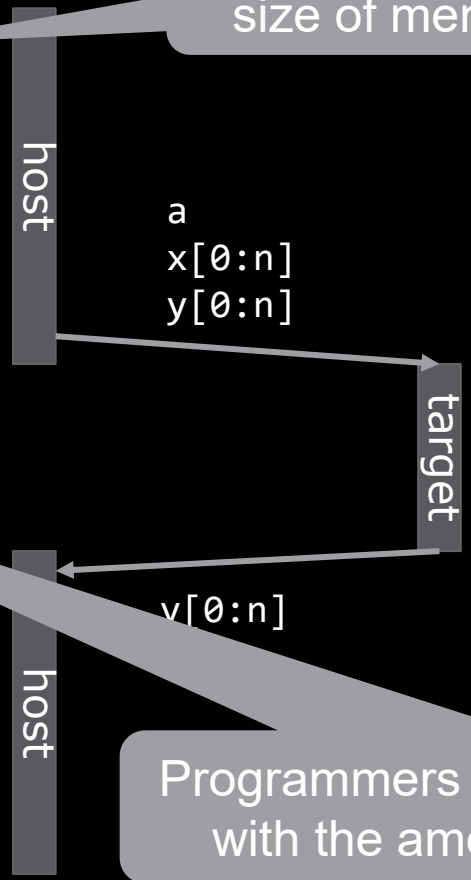


- Connections between host and accelerator are typically lower-bandwidth, higher-latency interconnects
  - Bandwidth host memory: hundreds of GB/sec
  - Bandwidth accelerator memory: TB/sec
  - PCIe® Gen 4 bandwidth (16x): tens of GB/sec

- Unnecessary data transfers must be avoided, by
  - only transferring what is actually needed for the computation, and
  - making the lifetime of the data on the target device as long as possible.

Example: saxpy

```
void saxpy(float a, float* x, float* y,
           int n) {
    double t = 0.0;
    double tb, te;
    tb = omp_get_wtime();
    #pragma omp target map(to:x[0:n]) \
                       map(tofrom:y[0:n])
    for (int i = 0; i < n; i++) {
        y[i] = a * x[i] + y[i];
    }
    te = omp_get_wtime();
    t = te - tb;
    printf("Time of kernel: %lf\n", t);
}
```



The compiler cannot determine the size of memory behind the pointer.

Programmers have to help the compiler with the amount of data to transfer.

OpenMP® Device Constructs: `target data`

- Create scoped data environment and transfer data from the host to the device and back
- Syntax (C/C++)

```
#pragma omp target data [clause[[,] clause],…]
structured-block
```

- Syntax (Fortran)

```
!$omp target data [clause[[,] clause],…]
structured-block
!$omp end target data
```

- Clauses

```
device(scalar-integer-expression)
map([{alloc | to | from | tofrom | release | delete}:] list)
if(scalar-expr)
```

Optimize Data Transfers

- Reduce the amount of time spent transferring data
  - Use `map` clauses to enforce direction of data transfer.
  - Use `target data`, `target enter data`, `target exit data` constructs to keep data environment on the target device (see next slide).

Create data environment.

```
void example() {
    float tmp[N], a[N], b[N], c[N];
    #pragma omp target data map(alloc:tmp[:N])  \
                            map(to:a[:N],b[:N]) \
                            map(tofrom:c[:N])
    {
        zeros(tmp, N);
        compute_kernel_1(tmp, a, N); // uses target
        saxpy(2.0f, tmp, b, N);
        compute_kernel_2(tmp, b, N); // uses target
        saxpy(2.0f, c, tmp, N);
}   }
```

No `map` clauses! Presence checks will find data via the pointer.

```
void zeros(float* a, int n) {
    #pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        a[i] = 0.0f;
}

void saxpy(float a, float* y, float* x, int n) {
    #pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        y[i] = a * x[i] + y[i];
}
```

Unstructured Data Regions

- Some programming styles such as C++ classes are difficult to enclose in a structured data region
- **Unstructured data regions** with the target enter/exit data were added to the standard to handle these cases
- Often, the target enter data will be right after allocation. And the target exit data will be right before the free.

```
float *tmp, *a, *b, *c;
int main(int argc, char *argv[]) {
    int N = 100;
    tmp = (float *)malloc(N*sizeof(float));
    a = (float *)malloc(N*sizeof(float));
    b = (float *)malloc(N*sizeof(float));
    c = (float *)malloc(N*sizeof(float));
    #pragma omp target enter data \
       map(alloc:tmp[:N], a[:N], b[:N], C[:N])
        zeros(tmp, N);
        compute_kernel_1(tmp, a, N);
        saxpy(2.0f, tmp, b, N);

        compute_kernel_2(tmp, b, N);
        saxpy(2.0f, c, tmp, N);

    #pragma omp target exit data map(delete:tmp, a, b, c)
    free(tmp, a, b, c);
}
```

```
void zeros(float* a, int n) {
    #pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        a[i] = 0.0f;
}

void saxpy(float a, float* y, float* x, int n) {
    #pragma omp target teams distribute parallel for
    for (int i = 0; i < n; i++)
        y[i] = a * x[i] + y[i];
}
```

OpenMP® Device Constructs: `target update`

- Issue data transfers to or from existing data device environment
- Syntax (C/C++)

```
#pragma omp target update [clause[[,] clause],…]
```

- Syntax (Fortran)

```
!$omp target update [clause[[,] clause],…]
```

- Clauses

```
device(scalar-integer-expression)
to(list)
from(list)
if(scalar-expr)
```

Example: target data and target update

```
#pragma omp target data map(alloc:tmp[:N]) map(to:input[:N]) map(from:res)
  {
#pragma omp target
#pragma omp teams distribute parallel for simd
    for (int i=0; i<N; i++)
      tmp[i] = some_computation(input[i], i);

    update_input_array_on_the_host(input);

#pragma omp target update to(input[:N])

#pragma omp target
#pragma omp teams parallel for simd reduction(+:res)
    for (int i=0; i<N; i++)
      res += final_computation(input[i], tmp[i], i);
  }
```

Review of Data Movement/ Management pragmas and clauses

`map(to:var[0:n]), map(from:var[0:n]), map(tofrom:var[0:n])` can be added to any compute directive

- Structured data regions – a block of code in a functional unit that will have data mapped over at the start and mapped back at the end

```
#pragma omp target data map(to:x[0:n]) map(from:y[0:n])
```

- Unstructured data regions are more flexible and can be done after array creation on the host and just before freeing the memory

```
#pragma omp target enter data map(alloc:var[0:n])
#pragma omp target exit data map(release:var[0:n])
```

- Updating data from host to device or vice-versa

```
#pragma omp target update to(var)   -- host to device
#pragma omp target update from(var) -- device to host
```

GPU and APU Programming model with OpenMP

CPU CODE

```
!allocation on host
ALLOCATE(var(1:N))

!compute on host
!$omp parallel do &
!$omp  private(i), shared(var)
DO i=1,N
   var(i) = …
END DO
!$omp end parallel do
!sync barrier at omp end …
…
!deallocation
DEALLOCATE(var)
```

DISCRETE GPU CODE

```
!allocation on host
ALLOCATE(var(1:N))

!compute on device, expl. mem movement!
!$omp target teams distribute parallel do &
!$omp  map(tofrom:var) private(i),shared(var)
 DO i=1,N
   var(i) = …
 END DO
!$omp end target teams distribute parallel do
!host-device sync barrier at omp end …
…
!deallocation
DEALLOCATE(var)
```

Costly to switch CPU -> GPU!

APU CODE

```
!$omp requires unified_shared_memory
!allocation of unified m
ALLOCATE(var(1:N))

!compute on device, no expl. mem movement!
!$omp target teams distribute parallel do &
!$omp             private(i),shared(var)
 DO i=1,N
   var(i) = …
 END DO
!$omp end target teams distribute parallel do
!host-device sync barrier at omp end …

!deallocation of unified memory
DEALLOCATE(var)
```

Cheap CPU -> GPU copy with APU

- Compute kernel
- Special directive to enable unified memory
- ~~Explicit memory management between CPU & GPU~~ -> not needed for APU!
- Synchronization Barrier

Exercises Introduction to OpenMP Offload

https://github.com/amd/HPCTrainingExamples/tree/main/Pragma_Examples

C/C++ exercises:
Pragma_Examples/README.md (Instructions for Introduction to OpenMP in the first sections)
Pragma_Examples/OpenMP/C/ (Code)

Pragma_Examples/OpenMP/CXX/ (Code)

Pragma_Examples/OpenMP/C/USM (Example code for #pragma omp requires unified_shared_memory and XNACK=0 or 1 behaviour)

Fortran exercises:

Pragma_Examples/OpenMP/Fortran/README.md

Further READMEs in sub-directories with guided exercises with and without XNACK=0 or 1

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